PROBABILITY BASED SERVICE LIFE PREDICTION OF REPAIRED CONCRETE ATTACKED BY CHLORIDE

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ABSTRACT

Recently, a wide array of research has been carried out to obtain more controlled durability and long-term performance of reinforcement concrete (RC) structures under a chloride attack environment. In particular, new in this study, service life was considered using the Montecarlo bootstrapping method to determine the beginning time of corrosion in repaired concrete. As a result of this analysis, the probability of corrosion is small for surface finishing material, followed by section restoration material, and remitar in the same conditions. Also, the probability of corrosion changes significantly with the thickness of repairing material. In particular, repairing is done when the probability of corrosion initiation is 10%, so the time for the structure to need repairing changes with the diffusion coefficient spread, with remitar being predicted at 16 years, section restoration material at 31 years, and surface finishing material, that as the greatest diffusion coefficient, predicted at 51 years.

1. INTRODUCTION

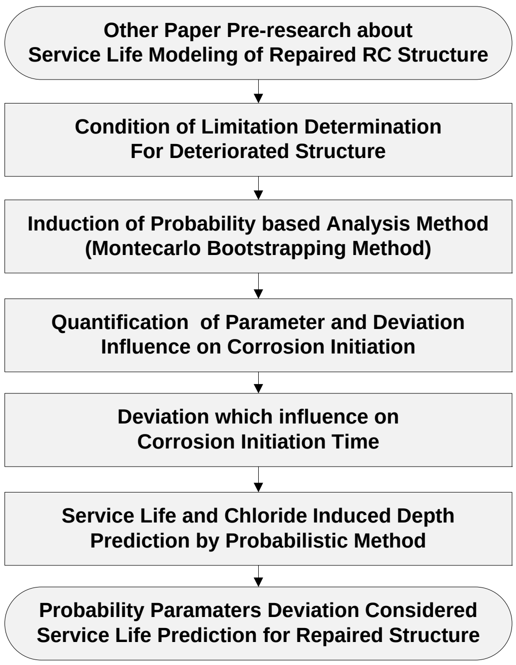


Figure 1. Flow of the research

For reasonable service life modeling, it is necessary to approach service life prediction in a scientific way. In particular, requirements of service life expansion make repairing attractive. In addition, as demand of concrete repairing increases dramatically, choosing the right repairing material becomes more important. Many research papers describe properties of repairing materials, but there are few that consider service life prediction.[1]-[3] Moreover, most predictions are based on deterministic theory; meanwhile chloride induced corrosion is hazardous due to parameters changes such as cover depth or diffusion coefficient. To overcome these problems, probability based service life model, being accepted by many researchers makes modeling safer and more accurate than the deterministic model. Therefore, in this paper, service life model for repaired concrete based on probability methods was considered to overcome problems mentioned before. To determine proper repairing time, each parameter in chloride attacked environments was considered using the Montecarlo bootstrapping method which is one well known probabilistic method. At this time, the diffusion coefficient was taken from other research papers.

2. CHLORIDE DIFFUSION IN REPAIRED CONCRETE

In most cases, theory of chloride diffusion in concrete is based on Fick's mathematical model. So, chloride induced corrosion initiation time was derived by Fickian heat equation. This determines chloride concentration C at time t, surface chloride concentration C_0, and depth from the surface point x. If C exceeded corrosion initiation concentration C_{lim}, then the structure estimated that corrosion has begun. In the case of repaired RC structures, C can be derived from equation [1] below as suggested

by JSCE (Japan Society of Civil Engineers).[5]

$$C(x, c_s, t, D_c, D_s) = C_0 \left\{ 1 - erf\left(\frac{0.1}{2\sqrt{t}} \right) \left(\frac{x}{\sqrt{D_c}} + \frac{c_s}{\sqrt{D_s}} \right) \right\} \quad [1]$$

In this situation, the concrete diffusion coefficient D_c can be calculated by a simple equation. However, as repairing materials have different properties than those of concrete, the diffusion coefficient cannot be calculated with this equation. Consequently, D_s values used here are taken from other research papers, obtained using experimental methods.

As mentioned above, the concrete diffusion coefficient D_c can roughly be determined by two different methods. First, the diffusion coefficient can be estimated using laboratory experiments. One of the most popular experimental methods is the Rapid Chloride Penetration Test (RCPT). This test needs just few days and it is a relatively simple process; so, many researchers and constructors chose this method. However, it needs proper specimens that can represent concrete used for construction. Specimens are picked out from the structure after casting and hardening in place. When the structure has operated for several years, and it is hard to know their mixing proportion property, this method is appropriate. The other method is making a specimen cylinder in a laboratory environment. When the mixing proportion of the structure is clearly known, this method is appropriate.

The Second method of determining concrete diffusion coefficient is calculation by equation [2].

$$D_c = 10^{4.5} \times (W/C)^2 + 0.14(W/C) - 8.47 \quad [2]$$

There is only one parameter in that equation, the water-cement ratio. This method is simple and does not need any experiment. It is very useful for durability design in new buildings before construction. This equation was derived from hundreds of thousands of experiments. However, this equation has a weak point in that it gives estimate of diffusion coefficient values relatively higher than real cast in place conditions. In spite of this problem, and because of convenience, this equation is widely used. Some researchers suggested using constants other than of $10^{4.5}$, 0.14, and -8.47.

3. ANALYSIS

This paper analyzes the sensitivity of each parameter affecting corrosion initiation. For this analysis, each parameter and its variations are taken from other research papers even though they must be accumulated results from experiments or actual surveys. That is because of lack of research. Therefore, deviation of each parameter is assumed to be a normal distribution in this paper.

Table 1 shows deviation of each parameter considered in this paper. Surface chloride concentration C_0, diffusion coefficient D_c, cover depth c, corrosion initiation concentration C_{cr} are those parameters. Additionally, corrosion initiation time was assumed when the probability of corrosion was over 10%.

When service life of repaired structure is predicted, it is best way using the data accumulated by long periods. However, as mentioned in the introduction, it is hard to find data about repairing materials. Therefore, experimental results were taken for consideration in this paper from other research papers.

Table 1. Parameters and deviations for probabilistic analysis

Parameter	Value/Deviation
$D_c(\times 10^{-12} m^2/s)$	N(5.31, 0.53)
x(cover, mm)	N(50, 5)
$C_{cr}(kgm/^3)$	N(1.2, 0.12)
$C_0(kg/m^3)$	N(9, 0.9)

3.1 Repairing materials

Corrosion initiation time was estimated when the structure was repaired with a different material. The Montecarlo Simulation (MCS) method was adopted and assumed that the diffusion coefficient of the repairing material is as shown in Table 2. There is no equation or suggestion to calculate D_s, therefore they are taken from other research papers.[3]

Table 2. Diffusion coefficient of repairing D_s material and deviation (cm^2/sec, $\times 10^{-8}$)

Repairing material	Diffusion coefficient/Deviation
Section restoration material	1.04, 0.10
Surface finishing material	0.46, 0.05
Remitar	3.77, 0.38

Figure 1 is the result from difference of repairing materials; i.e. all parameters are same except D_s. It predicts the time of corrosion rate at 10%. As a result, remitar repaired concrete structure will begin corrosion at 16 years. Meanwhile, section restoration repaired RC structure will begin at 31 years, finally remitar repaired structure will begin at 51 years. Remitar repaired structures will have the shortest service life compared with section restoration repaired structures and the longest service life will be surface finishing material repaired structures.

It can be presumed that service life will be dependent upon the diffusion coefficient even before making any prediction. The first consideration regarding repairing materials in figure 1 shows such a tendency. Increasing the diffusion coefficient brings not only a dramatic increase; it will be directly proportional to service life. i.e. if the diffusion coefficient doubles, then, service life will almost double too.

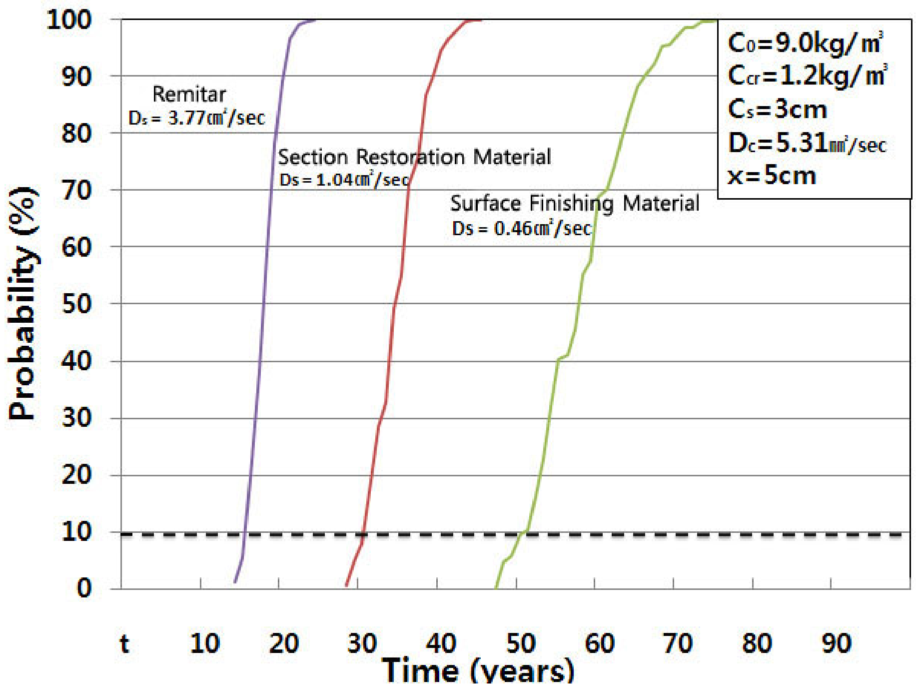


Figure 1. Corrosion initiation probability by time

This also shows that corrosion initiation time is flexible depending on the type of repairing material. And that can also have influence on the structure repairing time. Therefore, to prevent structure corrosion, increasing cover depth can be as good a solution as decreasing diffusion velocity, for example, using materials with lower diffusion coefficients for structures in marine environments; i.e. if the distance from chloride induce surface to rebar, it can reduce the depth of over corrosion initiation concentration in the same exposure time, also using lower chloride diffusivity materials is a good way to delay the corrosion initiation time.

On considering different types of repairing materials, the repairing depth of each material

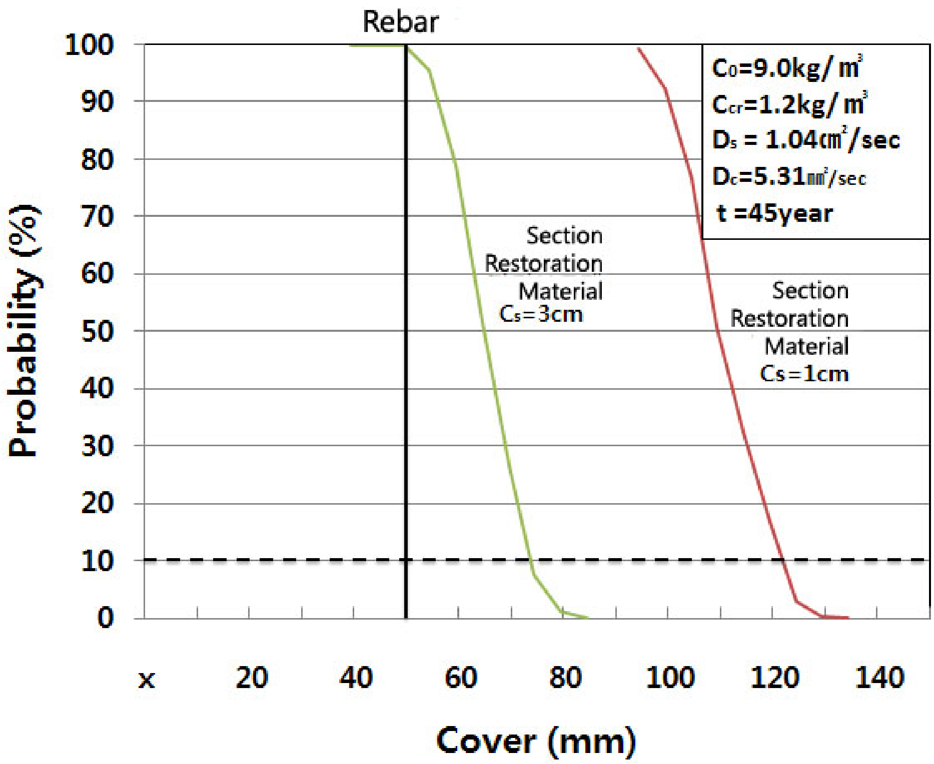
should be considered too. In order to perform an ideal repair; using minimum quantity of material, for example, this will be a necessary consideration. However, since there are few research papers focused on this point, there is not suitable comparison data with the results of this paper. To overcome this problem, more research should be done regarding properties of repairing materials and service life prediction methods.

Even though section restoration material, surface finishing material and remitar are used for the same purpose, structure repairing, their properties (especially, chloride resistance) are not the same. Therefore, even within the same time passage, their corrosion initiation rate must show different tendencies.

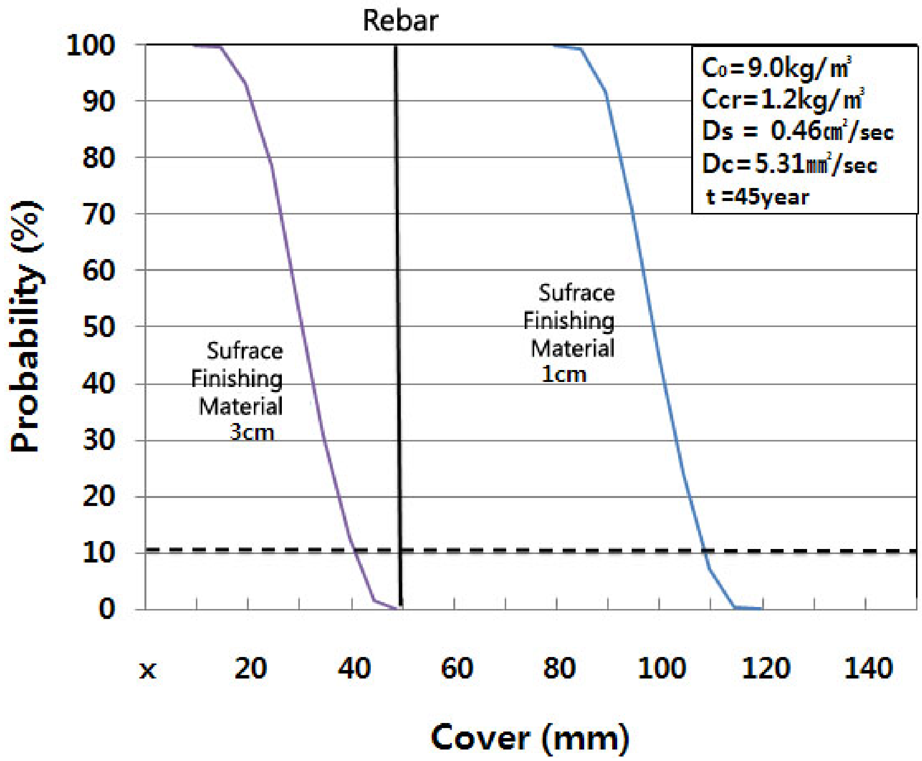
Figures 2-a) to c) indicate that each repairing material and cover depth makes different corrosion initiation rate when surface chloride concentration C_0 *is* 9.0 kg/m^3, corrosion initiation concentration C_{cr} is 1.2 kg/m^3, cover depth is 50 mm and the expected service life is 45 years. In the case of section restoration repaired structure (repaired cover, 10 mm and 30 mm), the corrosion rate will be 100% at the 45th year; i.e. the structure will be repaired with section restoration material which has better chloride resistance, over five times, than concrete. Figures 2-a) and 2-b) show the probability of chloride induced corrosion when concrete surface is covered with surface finishing material 10 mm or 30 mm. In this case, rebar will begin to corrode at a 100% rate when the repaired cover depth is 10 mm, on the other hand, at 30 mm of the surface finishing material is safe and its corrosion rate is almost 0%. Finally, figure 2-c) is the corrosion initiation probability of remitar when its repaired depth was 10mm or 30mm in the same way as was analyzed before. In that occasion, the probability of the structure starting corroding will be 100% even it was repaired by 30mm or remitar. With this consideration, 30 mm of repairing with remitar or section restoration material is not safe within 45 years when the structure is placed near the seashore and exposed to heavy sea environment.

Particularly, the corrosion initiation rate will be 100% at 80 mm from the surface, when the structure is repaired with 30 mm of remitar and 10 mm of section restoration material or surface finishing material. Most civil engineering structures have 80 mm, which means not only the architectural structure, but also the civil structure will be in serious danger.

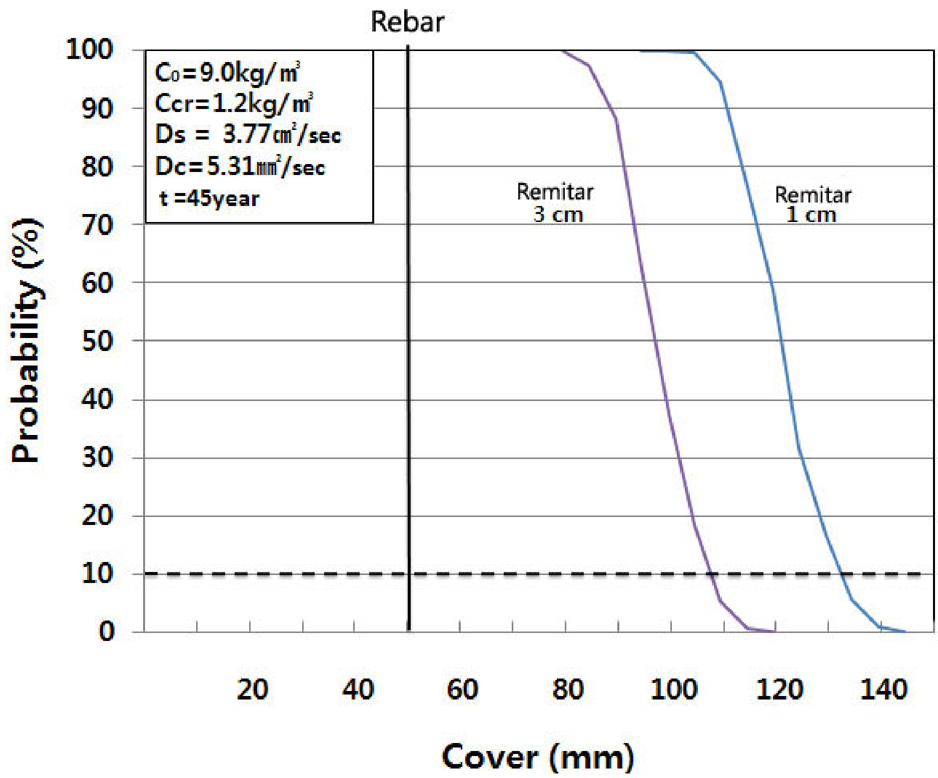
The other tendency is the gap between the repairing depth in the 3 cm line and 1 cm line in each graph. When the repairing material has better chloride resistance and lower diffusion coefficient, then the gap between two lines become closer. These situations are maybe caused by the velocity of chloride diffusion in concrete. To examine this rationale, more research will be needed. But, in the range of this research it is sure that the diffusion coefficient has influence on the delaying gap.



a) Section restoration material



b) Section restoration material



c) Remitar

Figure 2. Corrosion initiation probabilities by depth

Figure 3 shows the corrosion initiation rate of the section restoration repaired structure when the standard deviation is 5, 10 or 20%. The graph indicates that a wider range of standard deviation can bring out less accurate predictions. This means more accurate predictions are based on small variation ranges of each parameter. This also means that a wide range of parameter deviation will make difficult to predict the exact time of corrosion initiation. Inexact corrosion initiation time predictions will risk structure cracking, and it makes repairing construction more complicated and

require more working efforts. Consequently, having small deviation ranges is very important for service life prediction. That can be achieved from precise construction and good material quality. Especially concrete and repairing material quality are important. As it is already known, those materials are heterogeneous and their quality depends greatly on their condition, quality management should be done for successful maintenance of structures during their service life.

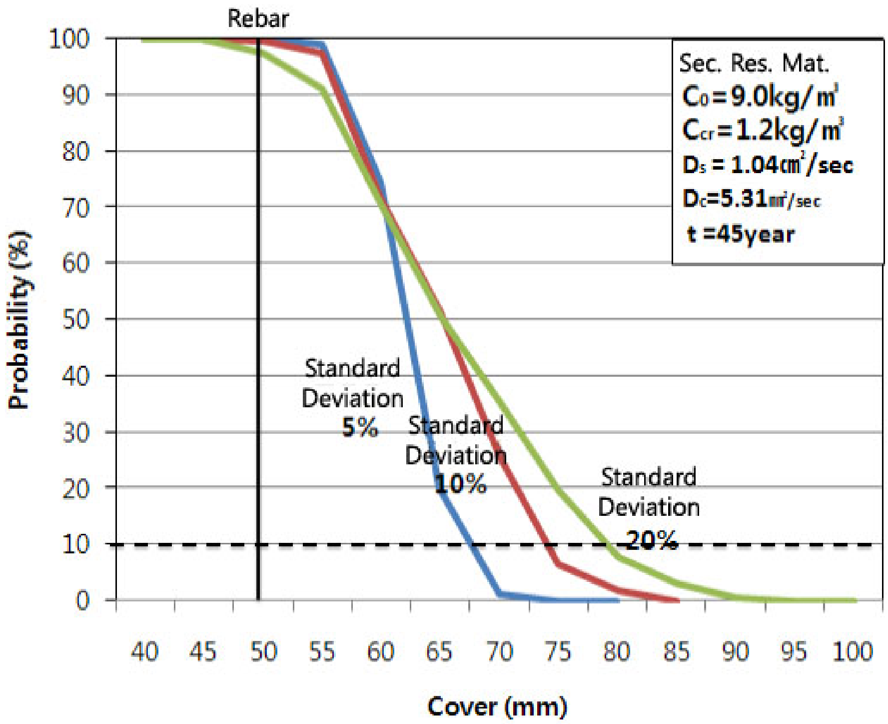


Figure 3. Corrosion rate depending on variation of standard deviation

3.2 Case Study

A virtual structure near seashore was set as a case study in order to test the application in a real world scenario. Conditions of the structure are stated in Table 3.

Surface chloride concentration was referenced from [Chapter of durability, Standard specification] published by the Korea Concrete Institute.[4] This paper assumes that the structure is built in a splash zone; at 5 m from the sea, rebar diameter is 30mm, water-cement ratio is 50% and expected service life is 100 years.

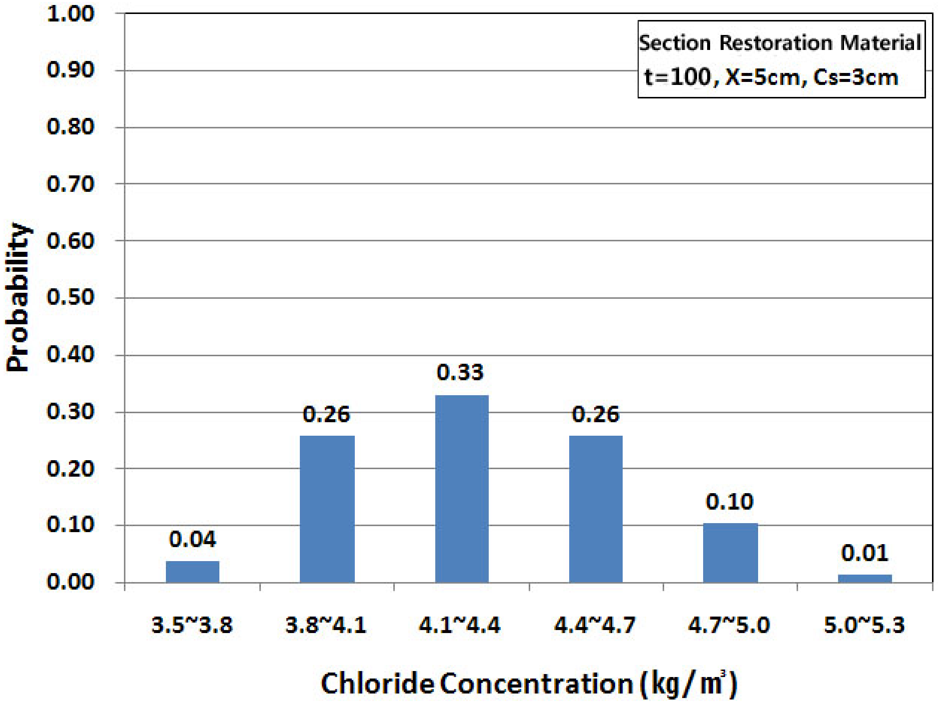
Table 3. Condition of the case structure

Conditions	Value
Distance from the sea	Within 5 m from the sea
Rebar diameter	30mm
W/C ratio	50%
Expected service life	100 years

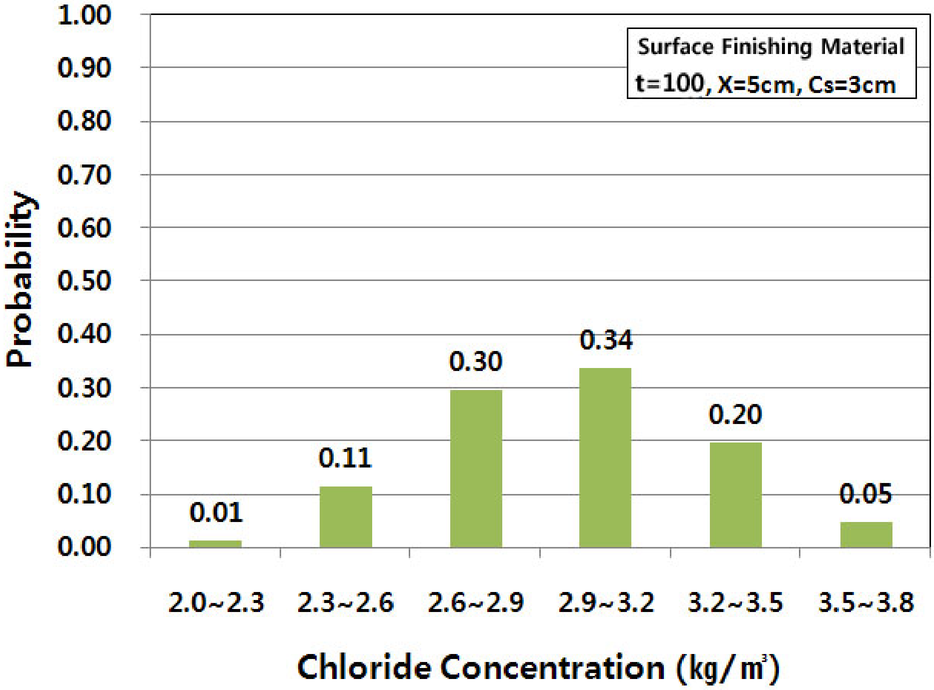
Table 4. Parameters and deviations for probabilistic analysis

Parameter	Value/Deviation
D_c(×$10^{-12}m^2/s$)	(5.31, 0.53)
x(cover, mm)	(50, 5)
C_s(mm)	(10, 1) and (30, 3)
C_{cr}(kg/m^3)	(1.2, 0.12)
C_0(kg/m^3)	(9, 0.9)

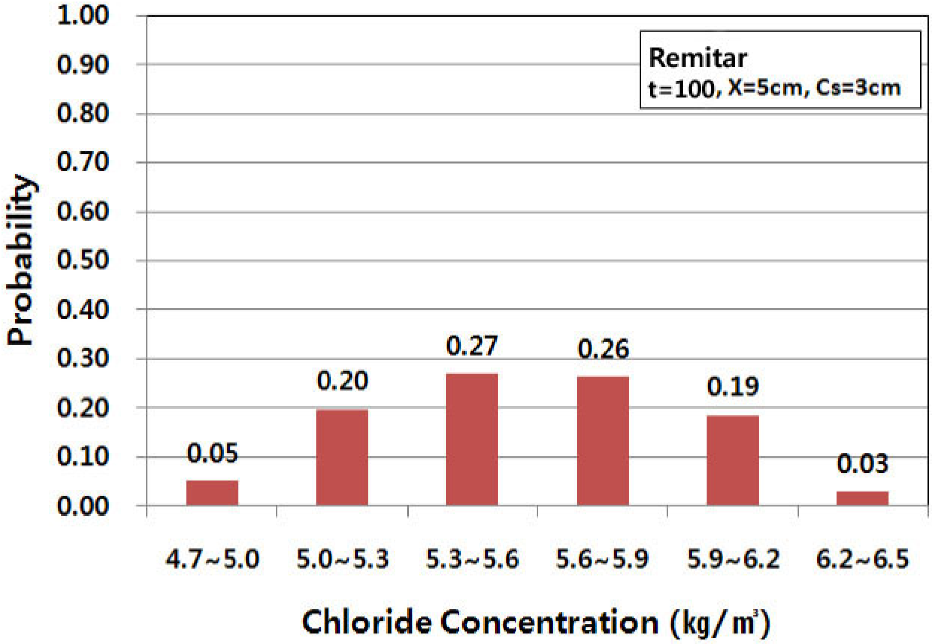
With the structure in specific conditions as assumed in Table 3, service life could be predicted as mentioned in Chapter 2. Diffusion coefficient of concrete and repairing material, cover depth, corrosion initiation concentration and repaired depth were parameters for service life prediction at that time. Section restoration material, surface finishing material and remitar were used for structure repairing. Concrete diffusion coefficient was calculated by a simple equation suggested in Korea standard specifications for concrete in this prediction.



a) Section restoration material



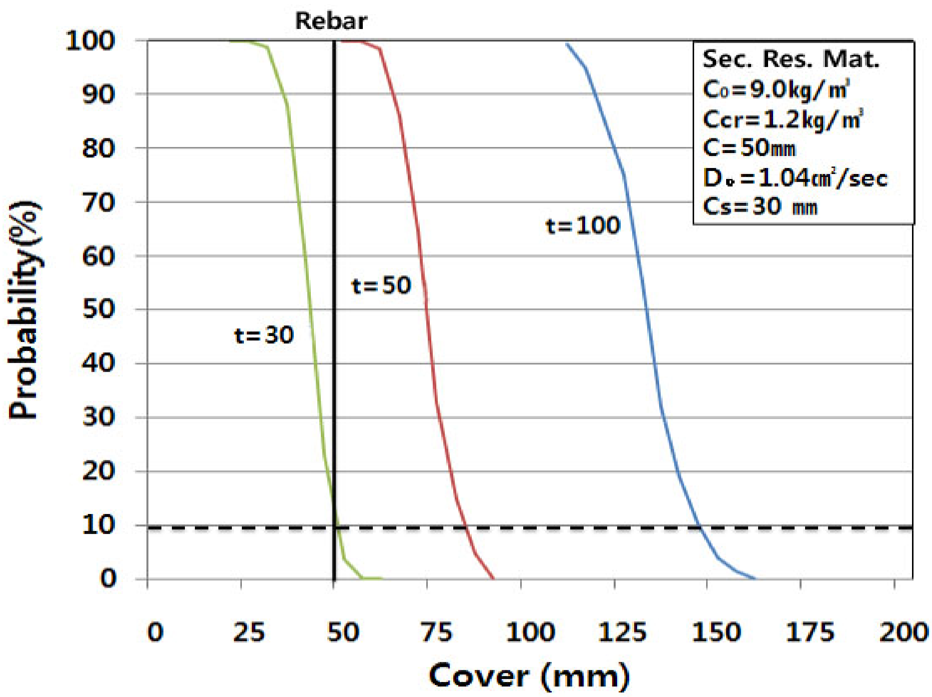
b) Surface finishing material



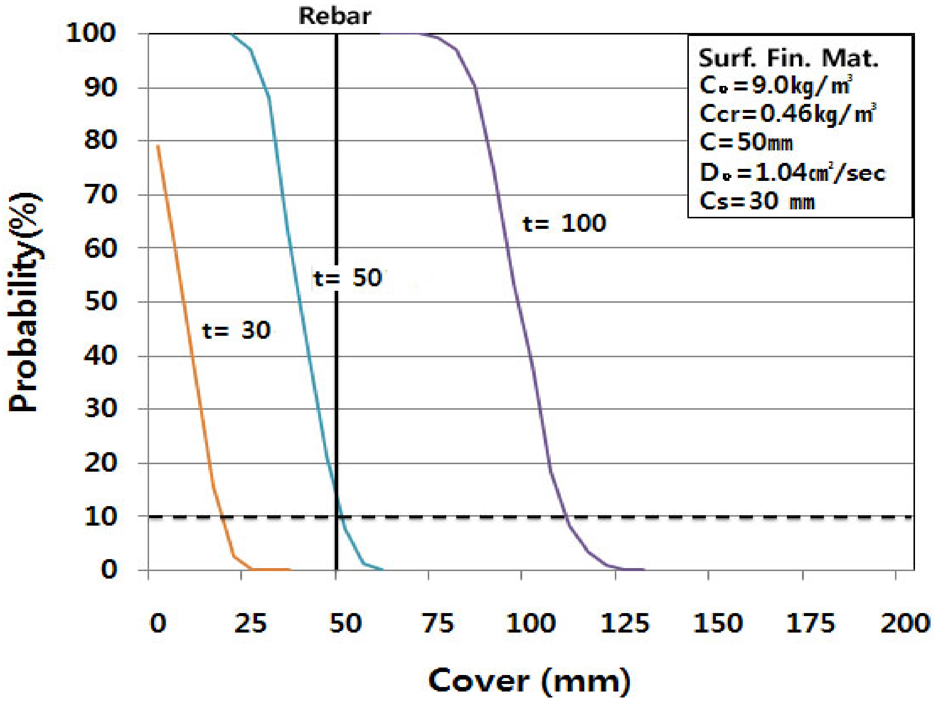
c) Remitar

Figure 4. Induced chloride distribution by type of repairing material

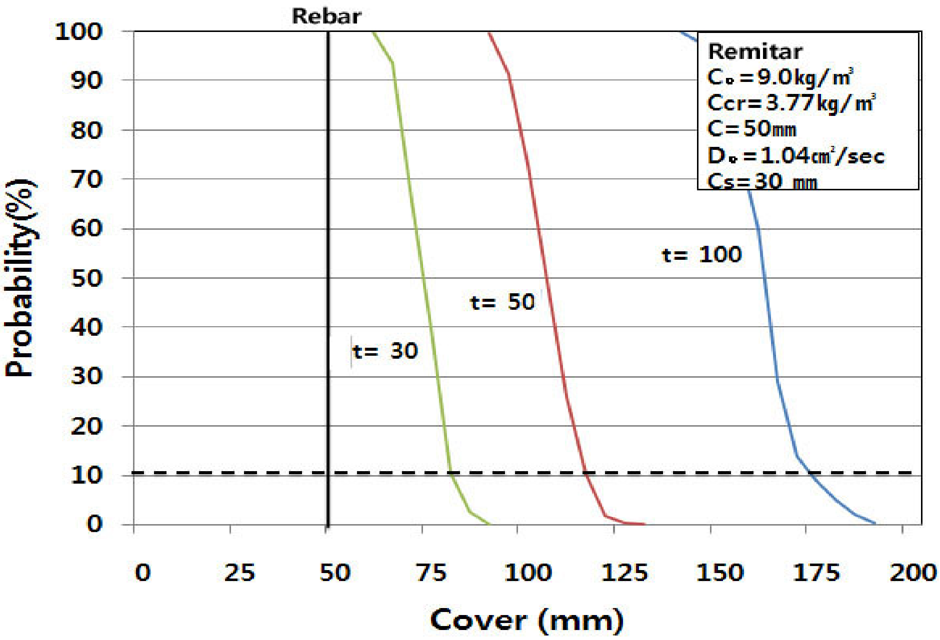
Figures 4-a) to c) show that in each case of the structure repaired using three different repairing materials, the repairing depth is 30 mm. The graph shows the distribution of induced chloride concentration at the position of rebar. In the case of the section restoration repaired structure, chloride concentration is distributed from a minimum of 3.6 kg/m^3 to a maximum of 5.3 kg/m^3 which exceeds 3 to 4 times the corrosion initiation concentration, 1.2 kg/m^3. Also, the surface finishing material repaired structure exceeds 2 to 3 times the corrosion initiation concentration; its distribution is from 2.0 kg/m^3 to 3.8 kg/m^3. Finally, in the case of remitar, induced chloride concentration is distributed from 4.7 kg/m^3 to 6.53 kg/m^3. They are 4 to 5 times larger than the corrosion initiation concentration. It can be known that a structure repaired only once cannot stand 100 years of service life. This consideration shows that even only 10% deviation can bring a wide range of chloride ingress distribution.



a) Section restoration material



b) Surface finishing material



c) Remitar

Figure 5. Corrosion initiation rate of each repairing material by time

Figures 5-a) to c) show the corrosion initiation rate of each repairing material and their conditions are mentioned as follows. C_0=9.0 kg/m^3, C_{cr}=1.2 kg/m^3, x=50 mm, c_s=30 mm and expected service life was 30, 50 or 100 years. End of service life was established by 10% corrosion rate.

Figure 5-a) shows the case of section restoration repaired structure. In that case, the structure service life ends at the 30th year. To obtain over 100 years of service life, more protection or repairs are necessary. If the structure is repaired with section restoration material again, repairing is required 3 times. In the case of surface finishing material, the structure will have the longest service life among the 3 cases. The 10% corrosion initiation rate will be reached at the 49th year. On the other hand, repairs with remitar structure start corrosion in a very short time after the operation. Rebar will begin to corrode at 100%. If the surface finishing material is used for repairing, repairing will be required only once, meanwhile remitar repaired structure needs at least 5 repairs.

To expand their service life, it must be known that using repairing material that has better

chloride resistance or increasing the repairing depth works too. Both ways indicate that decreasing the diffusion coefficient, i.e. velocity of chloride ion diffusion in concrete, effect plays a very important role in service life.

4. CONCLUSION

According to this research, it is known that the variation of each parameter has influence on service life prediction and their deviation can be considered by the MCS bootstrapping method. Therefore, this paper applied MCS to predict service life of the structure specially repaired ones. It can also improve reliability of service life prediction considering the heterogeneous characteristic of concrete and other materials or several errors can occur in real construction. The service life of structures in specific environments such as seawater splash zones was predicted in this paper. Conclusions are below.

1) If the corrosion rate at the end of service life was 10%, the structure repaired with 3 different materials each will have a different service life. In case of remitar repaired structures, which have the largest diffusion coefficient, its service life will end at the 16th year. Section restoration repaired structures will finish its service life at the 31st year and surface finishing repaired structures will stand out 51 years. Smaller diffusion coefficients will delay structure repair.

2) Not only the diffusion coefficient but repair depth has also huge influence on service life. When each repairing material was casted 10 mm or 30 mm, their service life hardly changed. Remitar repaired structures will have a 100% probability to begin corrosion both at 10 mm and 30 mm of repaired depth. Surface finishing repaired structure will have a 100% probability to begin corrosion with 10 mm of repaired depth; however, when repair depth increasing to 30 mm, the rate of corrosion initiation will decrease dramatically, so the structure will be safe relatively compared with other cases.

3) Further study needs to determine experimentally the diffusion coefficient of more repairing materials and that will become basic data of advanced research of service life prediction. Deviation of each parameter should be quantified. Service life prediction and research results of existing buildings data must be compared. That will help to improve the accuracy of service life prediction in repaired RC structure.

ACKNOWLEDGEMENT

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